

Leaching of Alachlor from Alginate-Encapsulated Controlled-Release Formulations†

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(Received 20 September 1995; revised version received 14 February 1996; accepted 22 May 1996)

Abstract: The mobility of alachlor from alginate-encapsulated controlled-release (CR) formulations was investigated in two contrasting soil profiles. Two CR formulations of alachlor were prepared with the following components (1) base—sodium alginate + kaolin + 'Tween' 20® (1 + 10 + 0.5 by mass) and (2) base + 40 g kg⁻¹ linseed oil. These were compared to technical grade alachlor and to a commercial alachlor EC formulation ('Lasso' 4EC). All herbicide treatments were labeled with [¹⁴C]alachlor and were applied to duplicate soil columns that were composed of a surface and a subsoil horizon. Each horizon was packed to a depth of 12.5 cm, giving a total column length of 25 cm. The columns were leached with 21 cm (420 ml) to 30 cm (600 ml) of 0.01 M calcium chloride for a period of 7 to 10 days. Alachlor leaching from the EC formulations was the same as that from the technical material in both soils: 33% in the Evesboro and 10% in the Conover soil. The CR-Oil formulation leached 4 and 2% of the applied [¹⁴C]alachlor, compared to 12 and 3% for the CR-N formulation for the Evesboro and Conover soils, respectively. The CR-Oil formulation also increased the amount of [¹⁴C]alachlor retained in the soil surface horizon (105–114%), compared to CR-N (39–45%), technical material (14–23%) and EC (12–17%).

Key words: herbicide, groundwater, mobility, linseed oil

1 INTRODUCTION

Alachlor is nonionic, acetamide herbicide that is used for control of annual grass weeds and certain broadleaf weeds in corn, soybeans and peanuts.¹ It is the third most widely used herbicide in the US, following atrazine and metolachlor, with an application of 22 500–25 000 tons in 1993.² Soil sorption of alachlor is dependent on soil type, with reported K_d values ranging from 0.52 for a low organic matter (0.5%), Norfolk sand to 13.5 for a high organic matter (8.7%), Cape Fear sandy loam.³ Alachlor is relatively nonpersistent, with reported half-life values ranging from 11.3 to 34.8 days at 25°C.⁴ In a recent well-water survey conducted by Monsanto,⁵ alachlor was detected in ~0.78% of those wells tested, while atrazine was detected in nearly 12%

of the wells. Alachlor has also been detected in surface waters. A recent study estimated that 18 tons of alachlor was discharged into the Gulf of Mexico from the Mississippi River and its tributaries in 1991.⁶ This was compared to 160 tons of atrazine, 71 tons of cyanazine and 56 tons of metolachlor. Although the detection frequency of alachlor is relatively low compared to other herbicides, concern is still warranted. This is primarily because alachlor is classified as a potential carcinogen (class B2), by the USEPA.⁷

In an attempt to reduce the amount of chemical pesticide used, several alternative weed control strategies have been investigated. Examples include biological control systems, integrated pest management and controlled release (CR) formulations. CR formulations may provide a viable, environmentally sound alternative to many of the current herbicide formulations.⁸ They have several advantages over standard herbicide formulations, including ease and safety in handling, reduced leaching potentials,^{9–11} and reduced volatilization

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potential.¹² Many procedures have been evaluated for the preparation of CR formulations. These include, but are not limited to, alginate encapsulation^{13,14} starch encapsulation,^{15,17} cyclodextrin complexation,^{18,19} and lignin entrapment.^{20,21}

Pepperman *et al.*²² have described a series of alginate-kaolin based metribuzin CR formulations. In a water-release study, the authors reported little effect on release of metribuzin from CR formulations due to alginate type or to various organic adsorbents. Greater control of release rates could be obtained with the addition of charcoal, although this resulted in some irreversible adsorption. In another water-release study,²³ the authors demonstrated that much greater control of metribuzin release rates could be obtained with the addition of linseed oil to the CR formulation. Controlled release of alachlor was also obtained with alginate formulations that contained linseed oil.²⁴ In this study the authors showed that release of alachlor could be slowed by aging the formulation or by increasing the oil/herbicide ratio. Several other oils, including canola, corn, olive, safflower, peanut, soybean and sunflower gave release rates similar to linseed oil.

The authors attributed their observations to a combination of effects. Light micrographs of CR formulations containing linseed oil have shown a polymeric film on the surface of the bead.²³ This would act as an additional diffusional barrier for the herbicide. Release of alachlor from the non-oil formulations is also controlled by diffusion; however without the linseed oil polymeric film the diffusion occurs more rapidly. It is also evident that a partitioning of the alachlor occurs between the linseed oil present in the formulation and the water surrounding the bead. This is supported by water-release experiments in which the established equilibrium has been disturbed.²³ In those cases, additional alachlor was released, until a new equilibrium point was established.

Riggle and Penner²⁰ investigated the controlled release of alachlor and metribuzin from pine kraft lignins, utilizing soil thin layer chromatography (STLC). The authors reported a significant decrease in the mobility of both alachlor and metribuzin on the STLC plates. Recently, the same authors studied the adsorption of metribuzin by various kraft lignins.²⁵ The authors reported that the controlled release properties of the lignins could be explained by a combination of effects that included adsorption of the herbicides to the lignin surfaces and macromolecule formation. Street *et al.*²⁶ investigated the effects of several adjuvants, including linseed oil, on the behavior of metribuzin in soil. Linseed oil was found to reduce metribuzin mobility slightly on STLC plates when applied in combination with the adjuvant ARD 54. The combination of linseed oil and the adjuvants did not decrease soybean yield; however, linseed oil + ARD 1836 significantly decreased control of sicklepod at two locations.

Johnson and Pepperman^{9,10} investigated the leaching potential of both atrazine and metribuzin alginate-linseed oil CR formulations. Atrazine CR formulations with and without linseed oil leached significantly less than a liquid atrazine formulation on the technical material. In addition, a significantly greater percentage of the applied herbicide was retained in the soil surface with CR formulations. Recovery of [¹⁴C]atrazine from the soil ranged from 58 to 93% for CR formulations, compared to 5–6% for technical atrazine and 2–4% for a liquid formulation.⁹ CR formulations also reduced the leaching potential of metribuzin, although the decrease was much smaller with formulations that did not contain linseed oil. The CR formulation with linseed oil leached from 9 to 13% of the applied [¹⁴C]metribuzin in four soils, compared to 58–85% for the technical material, 43–91% for a liquid formulation and 41–53% for the CR formulation without oil.¹⁰ Enhanced retention of [¹⁴C]metribuzin in the surface soil was also observed with the CR oil formulation. Huang and Ahrens²⁷ investigated the field persistence and mobility of controlled-release, microencapsulated alachlor formulations, compared to conventional formulations. The authors reported that, compared to the conventional formulation, the controlled release formulation increased the alachlor concentration in the surface soil. Levels in the subsoil were not increased, suggesting that leaching of the herbicide was not increased. The authors also suggested that alachlor persistence was greater with controlled release formulations, which resulted in better weed control with controlled release formulations. The objective of the present study was to determine the mobility of alachlor from two alginate-encapsulated CR formulations, compared to that from a commercial liquid formulation and technical alachlor in soil column experiments.

2 MATERIALS AND METHODS

2.1 Soils

The soils investigated in this study were: an Ap and C horizon of an Evesboro loamy sand (coarse-loamy, siliceous, mesic Aquic Hapludult) from Sussex county, Delaware and an Ap and Btg horizon of a Conover loam soil (loamy, mixed, mesic Udollic Ochraqualf) from Ingham county, Michigan. Soils were air-dried and then crushed to pass a 4-mm sieve for column studies and to 2 mm for chemical and physical analysis. The following properties were determined on all soil horizons: particle size (soil texture) by the hydrometer method;²⁸ 0–33 bar moisture content by pressure plate analysis; soil pH (in deionized water); and organic matter by Walkley-Black wet oxidation.²⁹

Alachlor sorption K_d values were determined by a standard batch equilibrium method, with the exception

that the centrifuge tubes were pre-equilibrated with the [^{14}C]alachlor solution for 24 h prior to soil addition. This procedure was used to account for any sorption of the herbicide to the centrifuge tubes. Stock 10^{-4} M solutions were prepared in 0.01 M calcium chloride with technical and [^{14}C]alachlor to obtain an activity of 20000 Bq litre $^{-1}$. Twenty ml of [^{14}C]alachlor solution at concentrations of 15, 30 and 60 μM litre $^{-1}$ was added to polypropylene centrifuge tubes (50-ml), and the samples were equilibrated on a rotary shaker at a speed of 150 rev min $^{-1}$ for 24 h. An aliquot (0.2 ± 0.002 ml) was then taken with a micropipette from each sample and placed in scintillation fluid (4 ml Scintiverse TM E, Fisher Scientific) and counted on a Beckman LS 1800 liquid scintillation spectrophotometer. Counting efficiency was 90%. Soil (5 g) was then added to each tube and the samples were re-equilibrated at 150 rev min $^{-1}$ for an additional 24 h. After equilibration, the samples were centrifuged at 2000g for 0.5 h and the supernatant was analyzed by liquid scintillation techniques. The difference between the supernatant concentration and the amount of herbicide present after pre-equilibration was assumed to be sorbed (after correction for soil blanks). Results from the sorption studies are reported as linear adsorption coefficients (K_d), averaged across concentration.

2.2 Controlled release formulations

Technical-grade alachlor and [^{14}C]alachlor were obtained from Monsanto Inc., St. Louis, MO and Sigma Chemical, St. Louis, MO, respectively. A commercial alachlor EC formulation ('Lasso' 4EC) was obtained from Dr Clyde Dowler, USDA, ARS, Georgia Coastal Plain Experiment Station, Tifton, GA. Controlled release formulations were prepared by a method similar to that of Pepperman and Kuan²³ to contain 10 g kg $^{-1}$ sodium alginate ('Kelgin' MV, Kelco, Division of Merck and Company, San Diego, CA), 100 g kg $^{-1}$ kaolin (Thiele Kaolin Company, Wrens, GA), 5 g kg $^{-1}$ 'Tween' 20® (Sigma Chemical Co., St. Louis, MO) and technical and [^{14}C]alachlor. Technical and [^{14}C]alachlor were first dissolved in the 'Tween' 20®, water and linseed oil (if present). Kaolin was gradually added and the slurry was stirred on a magnetic stir plate for 1 h to obtain a homogenous mixture. The alginate was added slowly to prevent clumping, and the mixture stirred for 0.5 h. The formulation mixture was then dropped into the gellant solution (0.25 M calcium chloride) with the aid of a peristaltic pump (Manostat Cassette) at a rate of approximately 80 ml h $^{-1}$. The beads were dropped into the gellant solution in two batches of 0.25 h. After an additional 5-min period, during which the beads were allowed to harden further, they were vacuum filtered through Whatman #2 filter paper, rinsed with an additional 30 ml deionized water

and allowed to dry for 72 h. The first CR formulation (CR-N) consisted of only the base formulation components and contained 19.6 g AI kg $^{-1}$. The second formulation (CR-Oil) contained 40 g kg $^{-1}$ (of the formulation mixture) raw linseed oil (T&R Chemicals, Inc., Clint, Texas) in addition to the basic components and 16.5 g AI kg $^{-1}$.

2.3 Alachlor treatments

The herbicide treatments used in this study were radio-labeled with [^{14}C]alachlor. The treatments were applied at a rate equivalent to 40 kg AI ha $^{-1}$ with 49950 Bq per column. This rate was required primarily to achieve an adequate ^{14}C -labeling rate of the soil columns at this lower alachlor formulation loading rate ($\sim 1.5\%$ AI). This high rate would also simulate a worst case scenario in the field. For the technical material and CR formulations, technical and [^{14}C]alachlor were combined and for the EC treatments [^{14}C]alachlor was mixed with 'Lasso' 4EC.

2.4 Column and soil preparation

Soil columns were prepared from clear Plexiglas pipe, 5 cm ID \times 30 cm long. The columns were split longitudinally and resealed with silicone sealant and duct tape to allow easy sampling of the column after the leaching process was completed. The bottom of each column was covered with Whatman #4 filter paper, followed by a piece of 200-mesh stainless steel wire cloth. Each column contained a surface soil and a subsoil. The soil horizons were packed to a depth of 12.5 cm each, for a total of 25 cm. The soil columns were packed at the following bulk densities (ρ_b): Conover Ap, Btg ($\rho_b = 1.3$, 1.3 g cm $^{-3}$) and Evesboro Ap, C ($\rho_b = 1.5$, 1.5 g cm $^{-3}$). These bulk densities resulted in pore volumes of approximately 0.11 litre for the Evesboro soil and 0.13 litre for the Conover soil. The pore volume approximates the total volume of voids present in the soil, after correction for moisture content. Prior to application of the herbicide treatments, the columns were saturated with tap water *via* capillarity and then allowed to drain free for 24 h.

2.5 Chemical preparation and application

All herbicide treatments were applied to duplicate soil columns. The technical material and EC formulation were applied in methanol (5 ml) and deionized water (5 ml), respectively, in a cross-hatched pattern on the soil surface. The CR formulations were evenly distributed on the soil surface as determined by visual inspection. Note that none of the granules were applied in

direct contact with the column wall, to avoid bypass flow problems. After herbicide application, an additional 2 cm of air-dried soil was added to the top of the column, followed by a disc of Whatman #4 filter paper covering the applied herbicide treatments. This was done to prevent erosion of the soil surface. The herbicides were allowed to equilibrate with the soil for 24 h prior to initiation of the leaching procedure.

2.6 Leaching and leachate collection

The leaching solution used in all experiments was 0.01 M calcium chloride. This was used to simulate the soil solution and to prevent dispersion of the soil clays during the leaching procedure. The Conover soil was leached with 30 cm (600 ml) of solution over a period of 10 days (3 cm day⁻¹). Due to its higher leaching rate, the Evesboro soil was leached with 21 cm (420 ml) of solution over a period of 7 days (3 cm day⁻¹). Note that these rates did not result in ponding of either soil. The leaching solution was applied with a peristaltic pump. All treatments for a given soil were leached simultaneously. The time and volume of each leachate were recorded. An aliquot (0.2 ml) was then taken from the leachate and placed in scintillation fluid (4 ml) and analyzed by liquid scintillation techniques. At the termination of the leaching procedure, the columns were allowed to drain for 72 h.

2.7 Soil analysis

The columns were split vertically and the soil was removed in 5-cm increments, placed in plastic bags, mixed, labeled and sealed. Subsamples from each increment (0.3 g, oven-dried) were mixed with cellulose (0.5 g) and then oxidized with a Packard Instruments Tri-Carb B306 oxidizer. The [¹⁴C]carbon dioxide evolved from sample oxidation was trapped in Carbo-

sorb and mixed with Permafluor scintillation fluid for analysis by liquid scintillation counting.

2.8 Statistics

Alachlor breakthrough data were fitted to linear, quadratic and cubic equations. The best fit was selected based on comparison of r^2 and P values and an analysis of residuals. An analysis of covariance was then used to make pairwise comparisons between formulations for each soil. Soil distribution data were analyzed with a repeated measures analysis of variance, with soil and formulation as the subject effects and depth as the repeated measure.

3 RESULTS AND DISCUSSION

3.1 Herbicide sorption

Alachlor retention varied with the soil horizon investigated with K_d values ranging from 0.05 for the Evesboro C horizon to 1.20 for the Conover Ap horizon (Table 1). These values are consistent with those in the literature for similar surface soils. Peter and Weber³ reported alachlor K_d values of 0.52, 0.59 and 1.55 for a Norfolk sand, Augusta loamy sand and a Goldsboro sandy loam soil. Locke³⁰ reported an alachlor K_d of 3.42 for a Dundee silt loam soil with 25% sand and an organic carbon content of 1.02%. Sorption K_d values were positively correlated with organic matter content and silt content with r values of 0.99***, 0.95* and negatively correlated with sand content $r = -0.98^{**}$.

3.2 Herbicide leaching

Distinct differences were noted in the leaching patterns of the soils investigated. Averaged across formulation,

TABLE 1
Selected Properties of the Evesboro and Conover Soils^a

		<i>OM</i>	<i>Sand</i>	<i>Silt</i>	<i>Clay</i>	<i>0.33 Bar</i>		
<i>Soil series</i>								K_d
<i>horizon</i>	<i>pH</i> ^a	<i>(%)</i>				<i>Texture</i>	<i>(litre kg⁻¹)</i>	
<i>Evesboro</i>								
Ap	5.3	0.94	71	16	13	9.6	Sandy loam	0.58
C	5.3	0.24	81	6	13	8.2	Sandy loam	0.05
<i>Conover</i>								
Ap	6.6	1.79	60	20	20	20.6	Sandy loam	1.20
Btg	6.6	1.21	61	19	20	20.8	Sandy loam	0.90

^a pH = pH of 1:1 soil/deionized water suspension, OM = soil organic matter content, 0.33 Bar = water content (g 100 g⁻¹ dry soil) at 0.33 bar pressure, Texture = soil textural class, K_d = linear alachlor soil sorption distribution coefficient.

the ranking of the soils, in terms of percent [^{14}C]alachlor leached, was: Evesboro (20.5%) > Conover (6.7%). Marked differences were also observed in the leaching patterns of the formulations investigated. Averaged across soils the ranking of formulations, in terms of percent leached was: EC (22.4%) > technical material (21.7%) > CR-N (7.6%) > CR-Oil (2.7%).

The Evesboro soil is a coarse-textured, low organic carbon content, Atlantic Coastal Plain soil (Table 1). This soil has a limited ability to retain alachlor, (K_d values of 0.58 in the Ap horizon and 0.05 in the C horizon) (Table 1). For the alachlor EC treatment, ^{14}C was first detected in the leachate at approximately 0.12 litre or slightly over one pore volume (Fig. 1). The technical alachlor treatment was detected at 0.18 litre. The amount leached from both treatments increased steadily over time to approximately 33% by the termination of the experiment (3.8 pore volumes). There was no significant difference in the leaching patterns of the technical material and EC treatments. Both CR formulations leached significantly less than these two treatments. The observed leaching patterns were slightly different for the CR formulations. A small amount of [^{14}C]alachlor was detected at 0.06 litre, slightly above 0.5 pore volumes with the CR-Oil formulation. This is compared to 0.18 litre for the CR-N formulation (Fig. 1). However, the CR-Oil formulation leached only 4% of the applied [^{14}C]alachlor, significantly less than the 12% observed for the CR-N formulation.

The Conover soil is loamy, glacial till soil, with a relatively high organic matter content in the surface and subsoil (Table 1). The K_d values for this soil were 1.20 for the Ap horizon and 0.90 in the Btg horizon (Table 1). For this soil there were significant differences between all formulations, with the EC treatment resulting in the greatest leaching of the applied

[^{14}C]alachlor and the CR-Oil formulation with the least (Fig. 2). The technical material, EC and CR-Oil formulations were all detected in the leachate at 0.06 litre, slightly under 0.5 pore volumes. This increased to 10% for the technical alachlor and 11% for the EC formulation by the end of the experiment (4.6 pore volumes). For the CR-N formulation, ^{14}C appeared in the leachate at 0.12 litre. The total amount leached was 2% for the CR-Oil formulation and 3% for the CR-N formulation.

Several interesting trends appear in the herbicide leaching data. First, although both CR formulations were leached significantly less than the technical material or the EC formulation, there was also a trend in which the CR-Oil formulation resulted in significantly less leaching of alachlor than the CR-N formulation. These data are supported by the literature reports. Pepperman and Kuan²⁴ found that linseed oil significantly reduced the release rates of alginate-kaolin formulations in static water release studies. Johnson and Pepperman¹⁰ found that linseed oil significantly decreased the leaching of metribuzin from alginate formulations. Gish *et al.*³¹ found that starch encapsulation reduced leaching of atrazine compared to technical grade atrazine in soil columns. After 16.1 pore volumes, 35, 10, 3 and <1% of the available atrazine was leached from the technical grade, borate, pearl and waxy starch formulations, respectively.

There was also a trend indicating that some leaching, albeit very little, would occur with the CR-Oil formulation with the first leaching volume. The reason for this is not entirely clear. It is possible that some [^{14}C]alachlor was not completely incorporated in the CR formulation matrix and as a result was washed from the exterior of the formulation with the first leaching volume. It is also possible that the linseed oil is acting as a carrier of the [^{14}C]alachlor. Although linseed oil is

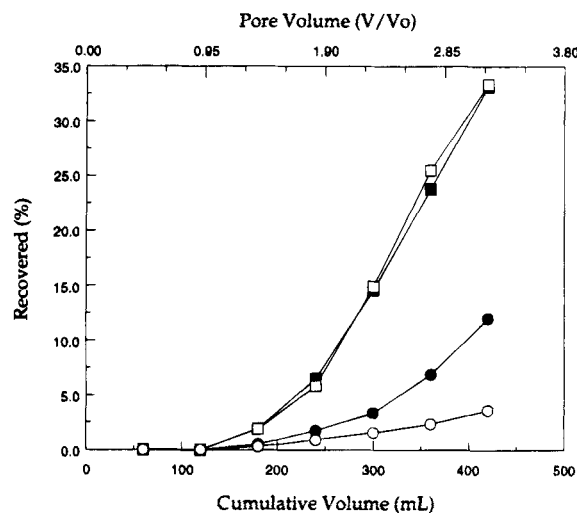


Fig. 1. Cumulative [^{14}C]alachlor leached from (■) technical material; (□) EC, (●) CR-N and (○) CR-Oil formulations in an Evesboro soil.

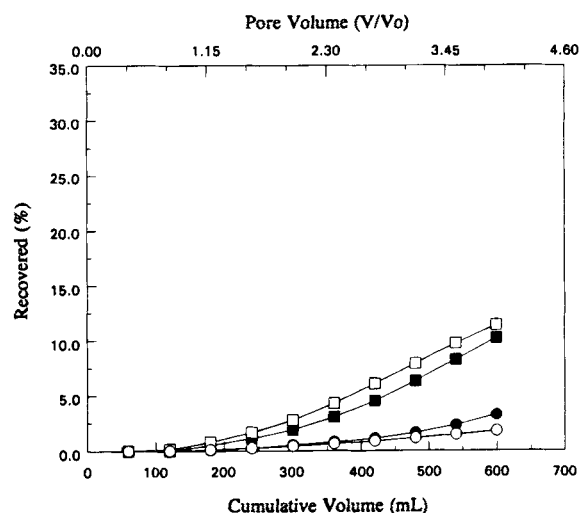


Fig. 2. Cumulative [^{14}C]alachlor leached from (■) technical material; (□) EC, (●) CR-N and (○) CR-Oil formulations in a Conover soil.

not miscible with water, it is possible that a small amount of oil containing alachlor was emulsified and transported during the leaching process. Despite these observations, the CR-Oil formulation consistently exhibited the smallest amount of total leaching of all the formulations investigated.

3.3 Herbicide distribution

The distribution of herbicides in the soil columns at the termination of the leaching procedure is presented in Table 2. Total recoveries (leached + extracted) of [^{14}C]alachlor from the soil columns varied by soil and formulation. The recoveries for the Evesboro soil were 87, 84, 90 and 130% for the technical material, EC, CR-N and CR-Oil formulations, respectively. For the Conover soil the recoveries were 80, 76, 85 and 123% for the same formulations. The high recoveries for the CR-Oil formulations are somewhat puzzling. It is possible that these are due to an inhomogeneity of oil incorporation in formulation matrix, resulting in variability of [^{14}C]alachlor content of the granules. This could result in a slightly higher than predicted application rate and the higher recoveries. This effect will be evaluated further.

In the Evesboro soil, the [^{14}C]alachlor remaining in the columns, as determined by combustion, from the technical material and EC formulation was similar. Approximately 54% of the applied [^{14}C]alachlor remained in the profile from the technical material and 51% from the EC formulation. Slightly higher levels were detected in the 5–10 cm section. It is apparent that the herbicide was moving through the column and that

further loss would have occurred if leaching was continued. Both CR formulations retained significantly more of the applied [^{14}C]alachlor in the surface (0–5 cm) layer, than the technical material and EC treatments (Table 2). The CR-Oil formulation retained a significantly greater percentage of [^{14}C]alachlor in the surface (0–5 cm) with 114%, compared to the CR-N (45%), technical material (14%) and EC (12%) treatments (Table 2). The remainder of the [^{14}C]alachlor from both of the CR formulations decreased uniformly with depth (Table 2).

The distribution of the technical material and EC treatments in the Conover soil was similar to that observed in the Evesboro soil with the exception that the levels of [^{14}C]alachlor were slightly higher, with 69 and 65% of the applied [^{14}C]alachlor remaining in the soil columns from the technical and EC treatments, respectively (Table 2). This is to be expected, as the Conover soil had a greater ability to retain alachlor, K_d values being approximately twice those of the Evesboro soil. A significantly greater amount of [^{14}C]alachlor was retained in the soil surface (0–5 cm) with the CR-Oil formulation, compared to the technical material, EC and CR-N formulations (Table 2). The [^{14}C]alachlor remaining in the soil profile from all four treatments tended to decrease with depth. It is apparent that additional herbicide loss for all formulations would have occurred if the leaching were continued.

Several researchers have demonstrated increased surface concentrations of herbicide with CR formulations. Johnson and Pepperman,⁹ found that CR formulations retained from 58 to 93% of the applied [^{14}C]atrazine in the soil surface in column experiments. Similar results were also obtained with CR metribuzin

TABLE 2
Distribution of ^{14}C from Alachlor Formulations in Two Soil Profiles as Estimated by Soil Combustion

Soil	Depth (cm)	Technical material	EC [^{14}C]	CR-N (%) ^a	CR-Oil
Evesboro	0–5	14.01c	12.06c	45.34b	114.44a
	5–10	16.10a	20.27a	18.53a	7.31b
	10–15	12.93a	9.85ab	8.77b	1.92c
	15–20	5.21a	3.95b	2.97b	1.16c
	20–25	5.57a	4.80a	2.40b	1.18c
Total % recovered in the leachate		33.17	33.38	12.01	3.59
Total % recovery		86.99	84.32	90.03	129.60
Conover	0–5	22.72b	16.89b	39.48b	105.32a
	5–10	19.66ab	15.63bc	25.95a	7.42c
	10–15	16.37a	14.83ab	9.02bc	4.36c
	15–20	6.67ab	10.54a	4.12b	2.45b
	20–25	3.65b	6.82a	2.90b	1.37b
Total % recovered in the leachate		10.21	11.41	3.25	1.78
Total % recovery		79.29	76.11	84.72	122.70

^a Means ($n = 2$) within a row followed by the same letter are not significantly different at $P = 0.05$

formulations that contained linseed oil.¹⁰ In that study the authors reported that the CR-Oil metribuzin formulations retained 13–27% of the applied [¹⁴C]metribuzin in the surface, compared to 2–5, 2–3 and 1–2% for CR-N, technical material and EC, respectively, Fleming *et al.*³² found that starch-encapsulated atrazine formulations would retain 80–99% of the applied herbicide in the top 5 cm of soil columns. This was compared to 5–13% for an atrazine SG formulation.

4 CONCLUSIONS

The CR-Oil formulation retained a greater percentage of the applied [¹⁴C]alachlor in the soil surface, than did the technical material, EC or CR-N formulations. The CR-Oil formulation also resulted in a decreased leaching potential for [¹⁴C]alachlor in both soils investigated, including a soil of high leaching potential. These combined effects would work together to decrease the groundwater leaching potential of the herbicide. Retention of the herbicide in the surface horizon is desirable for several reasons. First, it improves the efficacy against germinating weed seeds in this zone. Second, the herbicide is more likely to be degraded in this biologically active zone than in subsoils. It is also important, however, that the herbicide be available for weed control and not in a bound, unavailable form. Evidence from water release studies²⁴ and the breakthrough data from this paper indicate that the alachlor present in the CR-Oil formulation will gradually be released. Preliminary data from ongoing field experiments indicate that CR alachlor formulations will give weed control comparable to that with commercial formulations. Continued experimentation in this area is underway.

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